

# Properties of Thermal Photons at RHIC and LHC

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## Abstract

We study the emission characteristics of thermal photons at RHIC and LHC as affected by both the space-time evolution of the bulk medium and the thermal emission rates. For the former we compare the results of two evolution models (expanding fireball and hydrodynamics). For the latter, we detail the influence of hadronic emission components and study a speculative scenario by upscaling the default QGP and hadronic rates around the pseudo-critical region.

**Keywords:** QCD Matter, Ultrarelativistic Heavy-Ion Collisions, Thermal Photon Emission

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## 1. Introduction

The recent observations of a large enhancement of direct photons in heavy-ion collisions at RHIC [1, 2] and LHC [3] are indicative for thermal radiation off an interacting fireball of QCD matter formed in these reactions. It furthermore turns out that these direct photons carry a remarkable elliptic flow ( $v_2$ ) [4, 5], suggestive for prevalent emission from later stages in the fireball evolution, when most of the  $v_2$  of the bulk has already built up. Typically, this takes about 5 fm/c by which time the system (in semi-central Au-Au collisions at RHIC) has cooled down to near the (pseudo-) critical temperature,  $T_{pc} \simeq 170$  MeV, cf. Fig. 1 left. Assuming an average transverse-flow velocity of  $\beta \simeq 0.4c$  around this region yields a schematic estimate of the inverse-slope parameter of such a source of  $T_{\text{eff}} \simeq T_{pc} \sqrt{(1 + \langle v_T \rangle)/(1 - \langle v_T \rangle)} \simeq 255$  MeV, which is within the range of values measured by PHENIX [1, 2], see Fig. 1 [6]. Such a source is compatible with what has been deduced from other observables, e.g., for the quark distribution functions used in phenomenological coalescence models to reproduce the constituent-quark scaling of light and multi-strange hadron spectra and  $v_2$ , or for thermal dileptons, where large emission contributions from around  $T_{pc}$  [7, 8] explain the apparent dissolution of the  $\rho$  resonance from SPS to RHIC energies. Especially the latter is closely related to photons which correspond to the  $M \rightarrow 0$  limit of dileptons. This link has been explored in Ref. [6]; using a schematic fireball model for the bulk evolution with state-of-the-art photon rates, the direct-photon  $v_2$  turns out to be not far from the PHENIX data. In particular the hadronic rates are larger than in other calculations in the literature. Most notably, the  $M \rightarrow 0$  limit of the  $\rho$  spectral function [9] includes a rather extensive set of baryon-induced processes, known to be of critical importance for the low-mass dilepton enhancement [7]. In the following, we scrutinize these findings by testing various ingredients of the thermal photon calculations, both with respect to the space-time evolution (utilizing hydrodynamics with initial flow and sequential chemical and kinetic freezeout) and the photon rates (switching off the  $\rho$  spectral function contribution, and upscaling current QGP and hadronic rates around  $T_{pc}$ ) [10].

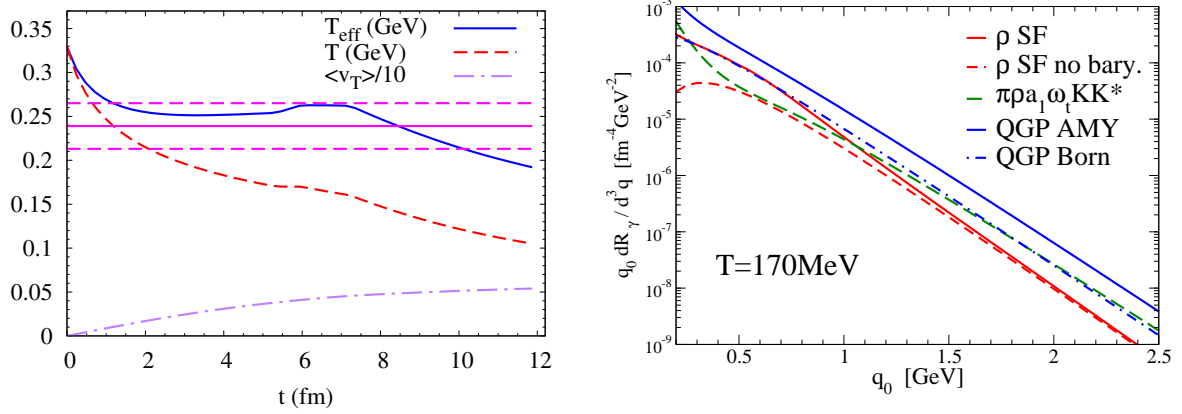


Figure 1. Left panel: time dependence of inverse slope parameter of the photon  $q_T$  spectrum (solid blue line), rest frame temperature (red dashed line) and average transverse expansion velocity (dash-dotted line) from a fireball evolution, compared to the measured inverse slope of the excess radiation in 0-20% Au-Au ( $\sqrt{s_{NN}}=200$  GeV),  $T_{\text{slope}}=(239\pm 26)$  MeV [2] (pink horizontal lines). Right panel: thermal photon production rates from the QGP (solid blue line: full leading order [11], dash-dotted line: Born rate [13]) and hadronic matter (red solid and dashed line:  $\rho$  spectral function contribution with and without baryons; long-dashed line: tree-level meson gas reactions [9]).

## 2. Thermal Emission Rates

In thermal field theory the equilibrium emission rate of photons,

$$q_0 \frac{dN_\gamma}{d^4x d^3q} = -\frac{\alpha_{\text{EM}}}{\pi^2} f^B(q_0; T) \text{Im} \Pi_{\text{EM}}^T(q_0 = q; \mu_B, T), \quad (1)$$

is determined by the in-medium photon selfenergy,  $\Pi_{\text{EM}}^T$ , due to the coupling to the partonic or hadronic constituents of the thermal bath. Its imaginary part represents the different cuts of the corresponding Feynman diagrams which characterize the scattering processes for thermal photon production.

For photon emission from the QGP we employ the complete leading-order results of Ref. [11]. For emission from hadronic matter we employ the zero-mass limit of the  $\rho$  spectral function of Ref. [12] which includes baryon and meson resonances resulting in pertinent Dalitz decays, as well as pion-exchange reactions with baryons generated by the in-medium pion cloud; in addition, pion, kaon,  $a_1$  and  $\omega$   $t$ -channel exchange reactions in a  $\pi\rho KK^*$  gas (not included in the  $\rho$  spectral function) have been added through pertinent Born diagrams using the standard kinetic theory expression [9]. These rates are summarized for a temperature of  $T=170$  MeV and vanishing baryon chemical potential ( $\mu_B=0$ ) in Fig. 1 right. Contributions from anti-/baryons in hadronic matter are significant up to rest-frame momenta of  $q_0 \leq 1$  GeV; for typical hadronic flow velocities at RHIC and LHC, this translates into lab-frame momenta of up to  $\sim 2$  GeV. Meson gas  $t$ -channel exchange reactions take over for  $q_0 > 1$  GeV. The sum of all hadronic processes is comparable to the perturbative QGP rates.

## 3. Space-Time Evolution

To model the space-time evolution of the thermal medium, over which the rates have to be integrated, we have considered two approaches: (i) an expanding fireball with ellipsoidal transverse area, assumed to be isotropic at each time step and with conserved total entropy [6]; (ii) a (2+1)-D ideal hydrodynamic model [15] based on the original code of Ref. [14]. Both models utilize the same equation of state (lattice EoS for the QGP with a near-smooth transition to a hadron resonance gas at  $T_{\text{pc}}=170$  MeV, followed by hadro-chemical freezeout at  $T_{\text{ch}}=160$  MeV), and have been adjusted to the same set of light and multistrange hadron spectra and  $v_2$ . Kinetic freezeout for multistrange hadrons has been imposed at  $T_{\text{ch}}$ , facilitated by a suitable transverse acceleration in the fireball model, and by a non-vanishing initial flow in the hydro model. For both models this implies that the bulk-medium  $v_2$  levels off close to  $T_{\text{ch}}$ , which, in turn, also helps in a better description of the pion and proton  $v_2$  at kinetic freezeout at  $T_{\text{kin}} \simeq 110$  MeV.

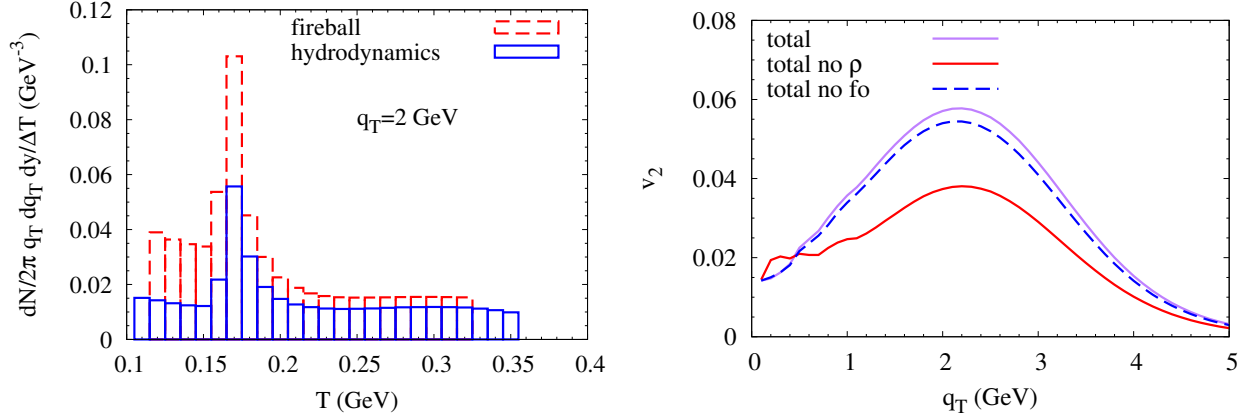


Figure 2. Left: temperature emission profile of thermal photon yields from fireball and hydro evolutions at  $q_T=2$  GeV. Right: reduction of the total direct photon  $v_2$  from the fireball when switching off the contributions from either the in-medium  $\rho$  spectral function or strong final-state decays.

#### 4. Photon Spectra and Flow

A detailed comparison of the photon spectra from the fireball and hydro evolution (using the same default rates, as plotted in Fig. 1) reveals a reasonable agreement (within ca. 20%) of the QGP spectra; both space-time models also exhibit a pronounced maximum of the temperature differential emission around  $T_{pc}$  up to momenta of at least  $q_T=2$  GeV, see Fig. 2 left. This is a consequence of the remnant of the latent heat in the transition region, i.e., the large variation in entropy density over a small range in  $T$  (similar to low-mass dileptons). However, in the hadronic phase, the hydro emission falls significantly below the one from the fireball, more so at higher momenta (up to ca. 50% at  $q_T=2$  GeV in Au-Au at RHIC). Part of the reason is the continuous freeze-out of the hydro medium, while the entire fireball volume only freezes out at the end of the evolution. While the latter is clearly an over-simplification, one should note that hadrons which are frozen out on the hydro hypersurface never re-thermalize, although, in principle, they could be reabsorbed by the freeze-out front. Therefore, we expect the most realistic hadronic emission in between the hydro and fireball results. We believe that another part of the discrepancy in the hadronic photon emission spectra, which becomes more pronounced toward higher  $q_T$ , is the “inward” burning of the freeze-out front. This leads to rather low-flow hadronic freeze-out cells especially toward the end of the evolution. On the contrary, the outward moving fireball front implies a monotonously increasing average flow (cf. Fig. 1 left). The “inward burning” of the hydro was identified as a possible problem in reproducing the measured HBT radii of pions. The initial flow introduced into our hydro evolution helps with this, but possibly not enough.

As a result of the discrepancy in the hadronic emission, the total direct-photon spectra from the hydro evolution (plus primordial photons) in 0-20% Au-Au at RHIC are below the fireball results by a few tens of percent in the region where thermal radiation is prevalent. Likewise, the maximum in the photon  $v_2$  is about 25% smaller for the hydro evolution. Yet our hydro results for the photon  $v_2$  are not far from the lower limit of the error bars of the PHENIX data, especially when allowing for moderate modifications of the primordial contribution, see Fig. 3 right. This constitutes an improvement over existing calculations. We attribute the main differences to the larger hadronic emission rates, the initial flow in the hydro evolution, and the strong-decay feeddown (e.g.,  $\Delta \rightarrow N\gamma$ ,  $a_1 \rightarrow \pi\gamma$ , etc.) in our calculation. For example, when switching off the (hadronic) photon contributions from the in-medium  $\rho$  spectral function, the maximum total direct-photon  $v_2$  in the fireball calculation decreases by about 35%, while switching off the strong feeddown reduces it by nearly 10%, cf. Fig. 2 right. At the LHC, the stronger QGP dominance renders closer agreement between hydro and fireball results. Both calculations tend to underestimate the preliminary ALICE  $q_T$  spectra, but agree with the preliminary  $v_2$  data within experimental errors.

Since the default thermal emission rates do not fully account for the observed direct-photon enhancement, we investigated an extreme scenario of upscaling our rates by a factor reaching a maximum of 3 around  $T_{pc}$  (“pseudo-critical enhancement”), and convoluted these rates over the hydro medium. This basically resolves the discrepancies with both RHIC and LHC spectra and  $v_2$ , see, e.g., the dash-dotted lines in Fig. 3. However, it is presently un-

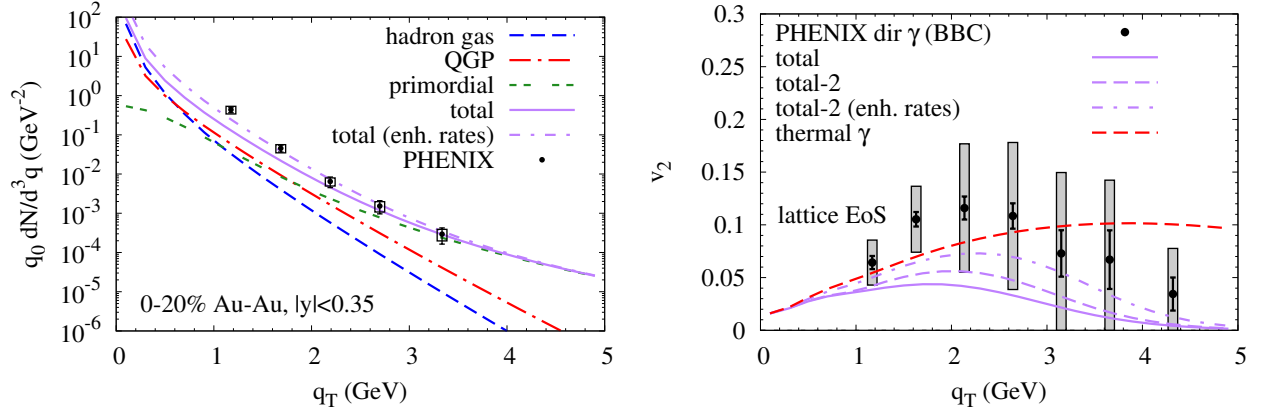


Figure 3. Direct photon spectra (left) and elliptic flow (right) from the hydrodynamic evolution using the default emission rates with the PHENIX pp reference for primordial emission (solid lines), with a pQCD-motivated primordial emission (dashed line in the right panel), and with “pseudo-critically” enhanced rates (see text for details) with pQCD primordial (dash-dotted lines). PHENIX data are from Refs. [1, 4].

clear whether such an enhancement can be substantiated by microscopic rate calculations, and, if confirmed, what ramifications this would have for dilepton observables (where current theory and data agree [8]).

## 5. Conclusions

We have computed thermal photon spectra and  $v_2$  in heavy-ion collisions at RHIC and LHC, using state-of-the-art thermal emission rates from QGP and hadronic matter including the effect of baryons which importantly figure in the dilepton context. We have compared two different evolution models based on the same EoS and fits to bulk-hadron data, as well as the concept of sequential freezeout. Their main difference appears in the hadronic emission spectra, which are larger in the thermal fireball than in the hydro evolution. Consequently, the fireball does slightly better in describing the experimental excess spectra and  $v_2$  of direct photons at RHIC, even though the hydro results are not far from the data either given their current uncertainties. At LHC, both models tend to underestimate the spectra but are compatible with the  $v_2$  from preliminary ALICE measurements. Important ingredients in our approach are large hadronic rates and a rapid built-up of radial flow (necessary to implement sequential freeze-out). An upscaling of the thermal rates around  $T_{pc}$  further improves the agreement, but a microscopic calculation of such an effect remains an open issue.

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